Modeling Vortex-Excited Vibrations of Axially Varying Cylindrical Structures In Non-Uniform Flow Fields

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LONG-TERM GOALS

Theoretical investigations have shown that wake-oscillator formulations of the vortex shedding process arise naturally as a consequence of weakly nonlinear and nonparallel instability modes in wake flows. We wish to explore the extension of wake-oscillator formulations to the modeling of vortex-excited vibrations of axially varying cylindrical structures in non-uniform flow fields. The issues to be addressed are threefold: (1) how best to incorporate axial diffusion of vorticity in wake-oscillator formulations; (2) what effect does the inclusion of axial diffusion of vorticity have on predicted structural responses; and, (3) how well do these predicted responses compare with available experimental data and with what generality.

OBJECTIVES

We intend to study first the behavior of a diffusive van der Pol oscillator as representative of the vortex shedding process from a cylindrical structure in a non-uniform flow field. The purpose of this investigation is to develop, through comparison with experimental results, a functional relationship between the diffusivity of vorticity and the shear in the flow field. Once this functional relationship has been developed, we intend to model vortex-excited vibrations of axially uniform cylindrical structures in non-uniform flow fields and to compare the predicted responses with experimental observations. This latter objective requires the development of a forced, diffusive van der Pol oscillator coupled to the structural equations of motion.

APPROACH

A forced, diffusive van der Pol oscillator can be constructed by adding fluid-structure interaction terms to the underlying diffusive van der Pol oscillator. The nature of these terms can be evaluated from experimental results for self-excited oscillations of uniform cylinders in uniform flows and from synchronization results for a rigid cylinder forced to oscillate in a uniform flow field. By then comparing the predicted behavior of the forced, diffusive van der Pol oscillator in a non-uniform flow field with corresponding experimental results, a functional relationship between the diffusivity of vorticity and the shear in the flow field can be developed.

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Once the appropriate relationship has been established, the diffusive van der Pol oscillator can be coupled to the structural equations of motion and the structural response to vortex shedding in a non-uniform flow predicted. The predicted responses will be compared with available experimental observations to ascertain how well and with what generality the experimental observations can be modeled.

WORK COMPLETED

We have completed the development of a forced, diffusive van der Pol oscillator for modeling the vortex shedding process from self-excited cylinders in a uniform flow field and from cylinders forced to oscillate in a non-uniform flow field. The forcing function has been evaluated so that model and experimental results are in agreement for the amplitudes of self-excited oscillations of uniform cylinders in uniform flows and for the synchronization boundaries for forced cylinders in uniform flows (Skop & Balasubramanian, 1997). The model has been used to simulate vortex shedding from a cylinder in a linearly sheared flow and a relationship has been established between the "turbulent" kinematic viscosity in the model and the shear parameter characterizing the flow (Skop & Balasubramanian, 1995). Using this relationship, the model has been used to simulate vortex shedding from tapered cylinders in uniform and shear flows. Excellent quantitative agreement between model simulations and experimental observations has been obtained (Balasubramanian et al., 1998).

The model represents the fluctuating lift coefficient C_L due to vortex shedding as

$$C_L(z,t) = Q(z,t) - \frac{2\alpha}{\omega_S}\frac{\partial Y}{\partial t}, \tag{1}$$

where the excitation component Q(z,t) of the lift coefficient satisfies the diffusive van der Pol equation

$$\frac{\partial^2 Q}{\partial t^2} - \omega_S G\,(C_{L0}^2 - 4Q^2)\frac{\partial Q}{\partial t} + \omega_S^2 Q - \nu_t \frac{\partial^3 Q}{\partial z^2 \partial t} = \omega_S F \frac{\partial Y}{\partial t}\ . \tag{2}$$

Here, z is the axial coordinate along the cylinder and t is time. Also C_{L0} is the fluctuating lift coefficient from a stationary cylinder and $\omega_S(z) = 2\pi\, SV(z)/D(z)$ is the local shedding frequency, where S is the Strouhal number, V is the local velocity, and D is the local diameter. Y(z,t) is the cylinder displacement normalized by D_{ref}, where D_{ref} is the cylinder diameter at the location of $\omega_{S,\,max}$. The parameters α, G and F are defined in terms of the structural mass and damping properties (Skop & Balasubramanian, 1997). The turbulent kinematic viscosity ν_t is given by (Skop & Balasubramanian, 1995)

$$\nu_t = 0.013\, L_\beta^2\, \omega_{S,max}\, \beta\ , \tag{3}$$

with the shear parameter β defined as

$$\beta = \frac{D_{ref}}{\omega_{S,max}}\left|\frac{d\omega_S}{dz}\right|. \tag{4}$$

The length of cylinder over which β is non-vanishing is denoted by L_β.

To obtain data against which to test the model, collaborative experiments with the University of Notre Dame have been carried out. The experiments examined the vortex-induced vibrations of uniform and non-uniform pivoted cylinders in uniform and shear flows. The experiments are detailed in Balasubramanian (1998) and also in Balasubramanian et al. (1998).

RESULTS

The experiments, for which the analysis and modeling have been completed, were for a uniform pivoted cylinder. For this system, $Y = \theta z / D_{ref}$ where θ is the angular displacement of the cylinder. The equation of motion for θ is

$$\frac{d^2\theta}{dt^2} + 2\zeta\omega_n \frac{d\theta}{dt} + \omega_n^2 \theta = \frac{\rho D}{2I}\int_0^L V^2 C_L z\, dz \ . \tag{5}$$

Here, I, ζ and ω_n are, respectively, the mass moment of inertia, damping ratio, and natural frequency of the pivoted cylinder. The length of the cylinder was L = 0.60 m and its diameter was D = 0.05715 m. Equations (1), (2) and (5) are integrated numerically for a given velocity field.

The linear shear profiles obtained during the experiments are shown in Figure 1. The velocity data is referenced to $V_{0.33}$, the measured velocity at z = 0.33 m from the top of the test section. The comparison between the experimentally observed amplitudes of oscillation in the lock-in regime and the numerically calculated amplitudes are shown in Figures 2a and 2b. The results for the maximum value of the shear profile at the free end of the pivoted cylinder correspond to Figure 2a; the results for the minimum value of the shear profile at the free end of the cylinder correspond the Figure 2b. The results are plotted versus the reduced velocity defined by $V_{0.53}/(f_n D)$ where $\omega_n = 2\pi f_n$. The peak amplitudes match the experimentally observed peak amplitudes; but the reduced velocities at which they occur differ slightly from the experiments. The experiments also show a more complex behavioral response than is predicted by the model. Additional details can be found in Balasubramanian et al. (1998).

IMPACT/APPLICATIONS

The successful prediction of the vortex-induced response of a uniform pivoted cylinder in a shear flow using a diffusive van der Pol oscillator as a model for the excitation component of the fluctuating lift force allows us to proceed to experimental and analytical studies of more complex systems. These systems include tapered pivoted cylinders in uniform and shear flows, uniform and tapered cantilevered cylinders in uniform and shear flows, and cables in shear flows. Quantitative agreement between experimental observations and model predictions in these cases would lead to the capability of predicting with good confidence the vortex-induced response of many offshore systems.

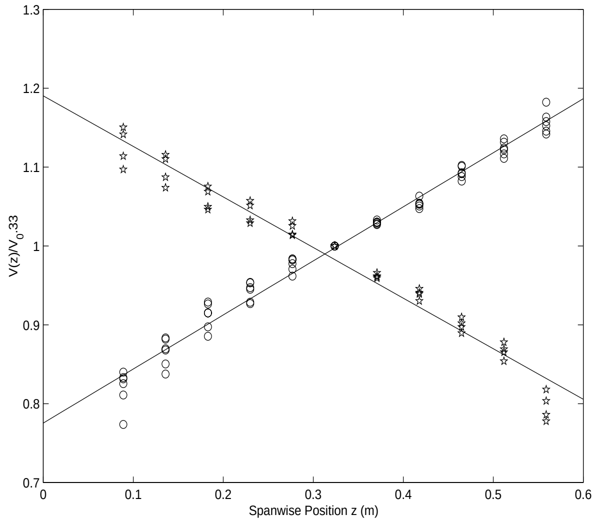
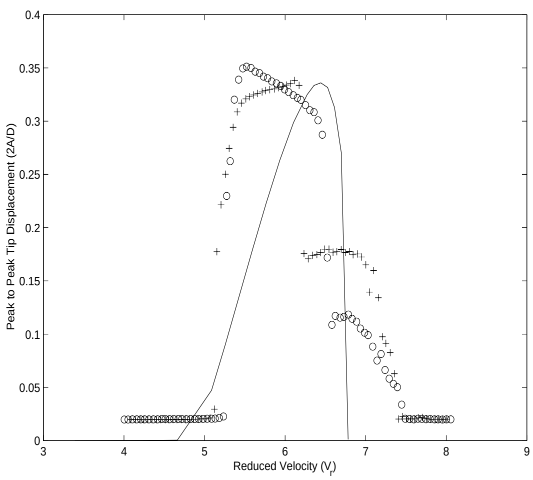
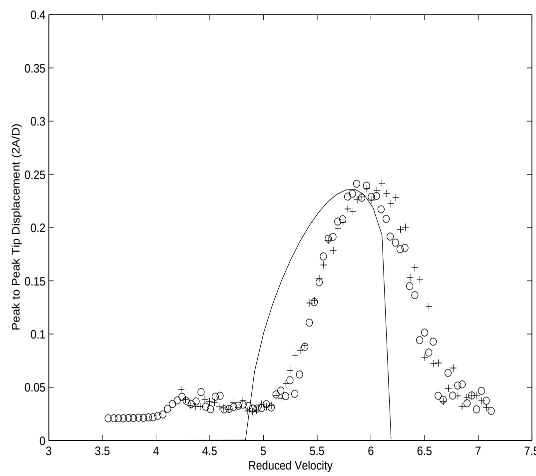


Figure 1. Linear shear profiles obtained during the experiments.
The solid lines are best fits to the data.



(a)



(b)

Figure 2. Comparison of numerically predicted response amplitudes and the experimentally observed amplitudes. (a) Maximum velocity at free end. (b) Minimum velocity at free end.

TRANSITIONS

No transitions have been accomplished to date.

RELATED PROJECTS

We are collaborating closely with the University of Notre Dame on their project "Experiments on vortex-excited oscillations of axially varying cylinders in shear flow," (Principal Investigator: Albin A. Szewczyk; Co-Principal Investigator: Richard A. Skop). We have also established contact with Pratap Vanka of the University of Illinois who is doing Direct Numerical Simulations of low Reynolds number vortex shedding from tapered cylinders.

REFERENCES

S. Balasubramanian, 1998. "Vortex-Excited Vibrations of Pivoted Cylinders in Uniform and Shear Flows," *Ph.D. Dissertation*, University of Miami.

S. Balasubramanian, F.L. Haan, A.A. Szewczyk and R.A. Skop, 1998. On "The Existence of a Critical Shear Parameter for Cellular Vortex Shedding from Cylinders in Non-uniform Flow," *Journal of Fluids and Structures*, **12**, 3-15.

S. Balasubramanian, R.A. Skop, F.L. Haan and A.A. Szewczyk, 1998. "Vortex-Excited Vibrations of Uniform Pivoted Cylinders in Uniform and Shear Flow," *Journal of Fluids and Structures*, in press.

R.A. Skop and S. Balasubramanian, 1995. "A Nonlinear Oscillator Model for Vortex Shedding from a Forced Cylinder. Part 2: Shear Flow and Axial Diffusion," *International Journal of Offshore and Polar Engineering*, **5**, 256-260.

R.A. Skop and S. Balasubramanian, 1997. "A New Twist on an Old Model for Vortex-Excited Vibrations," *Journal of Fluids and Structures*, **11**, 395-412.

PUBLICATIONS

Balasubramanian, S., 1998: Vortex-excited vibrations of pivoted cylinders in uniform and shear flows, *Ph.D. Dissertation*, University of Miami.

Balasubramanian, S., Haan, Jr., F.L., Szewczyk, A.A., and Skop, R.A., 1998: "An experimental investigation of the vortex-excited vibrations of axially-varying pivoted cylinders in uniform and shear flow", submitted for publication to the *Journal of Wind Engineering and Industrial Aerodynamics*.

Balasubramanian, S., Haan, F.L., Szewczyk, A.A., and Skop, R.A., 1998: On the existence of a critical shear parameter for cellular vortex shedding from cylinders in nonuniform flow, *Journal of Fluids and Structures*, **12**, 3-15.

Balasubramanian, S. and Skop, R.A., 1997: Modeling vortex-excited vibrations of uniform cylinders in uniform and shear flow, *Proceedings of ASME 4th International Symposium on Fluid-Structure Interactions, Aeroelasticity, Flow-Induced Vibration & Noise*, Dallas, TX.

Balasubramanian, S., Skop, R.A., Haan, F.L., and Szewczyk, A.A., 1998: Vortex-excited vibrations of uniform pivoted cylinders in uniform and shear flow, *Journal of Fluids and Structures*, in press.

Skop, R.A. and Balasubramanian, S., 1995: A nonlinear oscillator model for vortex shedding from a forced cylinder. Part 2: Shear flow and axial diffusion, *International Journal of Offshore and Polar Engineering*, **5**, 256-260.

Skop, R.A. and Balasubramanian, S., 1997: A new twist on an old model for vortex-excited vibrations, *Journal of Fluids and Structures*, **11**, 395-412.

Szewczyk, A.A., Balasubramanian, S., Haan, F.L., and Skop, R.A., 1997: Experiments on vortex-induced vibrations of pivoted circular cylinders, *Proceedings of ASME 4th International Symposium on Fluid-Structure Interactions, Aeroelasticity, Flow-Induced Vibration & Noise*, Dallas, TX.